

Acoustic Systems for the Measurement of Streamflow

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Acoustic Systems for the Measurement of Streamflow

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Acoustic Systems for the Measurement of Streamflow

By Antonius Laenen and Winchell Smith

Abstract

The acoustic velocity meter (AVM), also referred to as an ultrasonic flowmeter, has been an operational tool for the measurement of streamflow since 1965. Very little information is available concerning AVM operation, performance, and limitations. The purpose of this report is to consolidate information in such a manner as to provide a better understanding about the application of this instrumentation to streamflow measurement.

AVM instrumentation is highly accurate and non-mechanical. Most commercial AVM systems that measure streamflow use the time-of-travel method to determine a velocity between two points. The systems operate on the principle that point-to-point upstream traveltime of sound is longer than the downstream traveltime, and this difference can be monitored and measured accurately by electronics. AVM equipment has no practical upper limit of measurable velocity if sonic transducers are securely placed and adequately protected. AVM systems used in streamflow measurement generally operate with a resolution of ± 0.01 meter per second but this is dependent on system frequency, path length, and signal attenuation. In some applications the performance of AVM equipment may be degraded by multipath interference, signal bending, signal attenuation, and variable streamline orientation.

Presently used minicomputer systems, although expensive to purchase and maintain, perform well. Increased use of AVM systems probably will be realized as smaller, less expensive, and more conveniently operable microprocessor-based systems become readily available.

Available AVM equipment should be capable of flow measurement in a wide variety of situations heretofore untried. New signal-detection techniques and communication linkages can provide additional flexibility to the systems so that operation is possible in more river and estuary situations.

INTRODUCTION

Velocity measurement of fluids by acoustics had its major development in the fields of oceanography and pipeline hydraulics. Most theoretical work on acoustic propagation in water is found in oceanographic textbooks. Measurement of sound velocities, ocean currents, and ship speeds have been made by standard acoustical devices since the mid-1950's. Additional information on acoustic velocity measurement can be found in journal

articles dealing with pipeline flow. The increased use of pipelines for transport has provided incentive for the development of very accurate nonrestrictive flow-measuring devices. Acoustic velocity meter (AVM) development for the measurement of streamflow is an offshoot of pipeline flowmeter development.

Why Use an AVM?

The development of acoustics as a tool for stream gaging was stimulated by the desire to improve the accuracy of discharge measurement, and the need to compute discharge at sites where conventional techniques were not adequate. AVM systems are successful when a stable relation is developed between discharge and the velocity along the acoustic path. Measurement of discharge under conditions of variable backwater is one typical condition in which AVM's have been used successfully. Because increasing emphasis is being placed on the management of water resources, it is sometimes necessary to measure streamflow at sites where mechanical meters and stage-discharge relations are not sufficient. Why use an AVM? Because, if properly used, it can provide a high degree of accuracy and is capable of measuring in situations where path velocity and discharge relations can be developed.

Purpose

Very little information is readily available concerning the operation, applications, performance, and limitations of AVM equipment. The purpose of this report is to assemble both published and unpublished information in such a manner as to provide a better understanding of the application of this instrumentation to the measurement of streamflow. This report is intended to:

1. Show how the development of AVM systems by the Geological Survey fits in with other development both here and abroad, and with other applications.
2. Show where AVM equipment is used and list known manufacturers of streamflow-oriented systems.
3. Initiate those not familiar with traveltime equations and present other pertinent methods used in determining fluid velocity.
4. Discuss limiting acoustical criteria with respect to streamflow applications.
5. Discuss in detail, streamflow-oriented AVM systems maintained by the Geological Survey.
6. Present recent developments that will expand the knowledge of performance, limitations, and applications of AVM's.

SEQUENCE OF DEVELOPMENT

The following paragraph is a condensation of early AVM history extracted from an article by McShane (1971): The conception of the modern acoustic velocity meter can be attributed to a German named Oskar Ruten, who in a 1928 patent (fig. 1, from U.S. Scientific Library Patent and Trademarks Office, Arlington, Va.) described a traveltime-difference system requiring a center transmitter and two side receivers. The first usable device, however, was not developed until 1953, when a scientist, Henry Kalmus, in the Ordinance Electronic Research Branch of the National Bureau of Standards, set up acoustical test equipment. Among other things, the equipment was used to measure the flow of blood through small tubes inserted in the aorta of a patient. The first commercial instrument for measuring liquid flow was produced in 1955 by J. Kritz of Maxson Co.¹ who developed an instrument to monitor in-flight refueling operations for the U.S. Air Force. By 1955, development was in progress on acoustic velocity meters for industrial, medical, oceanographic, riverflow, and reactor applications. In all these areas, successful results were reported, and investigators were enthusiastic about the future of acoustical flow measurement. During this same period, the sing-around velocimeter became a standard instrument for sound velocity measurement in the ocean.

In 1957, the U.S. Geological Survey initiated a cooperative research program with the U.S. Army Corps of Engineers and the California Department of Water Resources, to develop a suitable flowmeter to measure the discharge in streams and channels subject to variable backwater. This study, which terminated in 1966 after the development of a workable prototype system, demonstrated that an AVM could be built and would be satisfactory for gaging flow in streams subject to variable backwater. The prototype systems were tested on the Delta-Mendota Canal near Tracy, Calif., and the Snake River near Clarkston, Wash. (Smith and Wires, 1967). These two systems worked just well enough to demonstrate the potential of open-channel acoustical flowmeters, but maintenance was an overwhelming problem.

Meanwhile, Westinghouse Electric Corp., with a good background in oceanographic-equipment manufacturing, began testing AVM designs in 1962. They installed their first AVM system in a penstock at Sommersville Dam in West Virginia in 1964. The Westinghouse design was well proven by 1967, when a contract was awarded to them by the U.S. Geological Survey and U.S. Army Corps of Engineers for a system on the Columbia River at The Dalles, Oreg. This installation began opera-

¹The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

tion in 1968 and became the first operational AVM in a large natural channel (Smith and others, 1971).

Research and development of AVM systems (commonly called ultrasonic flowmeters in foreign countries) were not confined to the United States during this period. From 1965 to 1970, Tokyo Keiki Co., Ltd., of Japan, installed acoustic meters in several hundred pipelines and in five small stream channels. In Europe, Krupp-Atlas of Germany, and the Atomic Energy Research Establishment (AERE) of England developed systems in the early 1970's. In the mid-1970's the Rijkswaterstaat of the Netherlands began development of a system. Today (1981), there are hundreds of acoustic meters in use in pipelines and large numbers in use in natural channels and canals throughout the world. Modern AVM's provide a continuous real-time output of river discharge suitable for operational purposes as well as normal recordkeeping functions.

EQUIPMENT AVAILABILITY

A survey of AVM equipment was made to determine state-of-the-art instrumentation, its use, and its availability. Table 4 (at back of report) lists 88 stream sites with AVM's that measure velocity over paths greater than 10 m in length. Several Russian AVM systems are known to exist, but no information was available for inclusion in the table. AVM systems in open channels and conduits with path lengths less than 10 m were too numerous to list.

Since the first installation of commercially available open-channel AVM's in 1967, two major advancements in electronics have been made: (1) the introduction of integrated circuitry and (2) the introduction of the silicon memory chip. For all practical purposes, there have been three generations of AVM equipment that coincide in time with the major advancements in electronics.

Westinghouse Electric Corp. equipment installed in 1967 consisted primarily of separate function boards made up of transistor circuitry. Board functions were interactively connected to one another with many wires to form a circuit so that the required operations could be performed. This made the system configuration somewhat flexible but difficult to operate and troubleshoot. The same basic design was used in the next generation of equipment which incorporated integrated circuits and increased the capacity for more paths and computational capabilities. This equipment, which was marketed as the Westinghouse 204 series, can now be purchased as their improved 601 series. Microprocessor design is used in the last generation of Westinghouse equipment and is marketed as the LFM 801 series.

In 1967, Ocean Research Engineering Inc. (ORE), produced a hard-wire system similar to the Westinghouse



DEUTSCHES REICH



AUSGEBEN AM
23. MÄRZ 1931

REICHSPATENTAMT
PATENTSCHRIFT

№ 520484

KLASSE 42e GRUPPE 23

R 75709 IX/42e

Tag der Bekanntmachung über die Erteilung des Patents: 19. Februar 1931

Dipl.-Ing. Dr.-Ing. Oskar Rütten in Berlin-Friedenau

Verfahren und Vorrichtung zum Messen von strömenden Flüssigkeits-,
Gas- oder Dampfmenngen

Patentiert im Deutschen Reiche vom 19. September 1928 ab

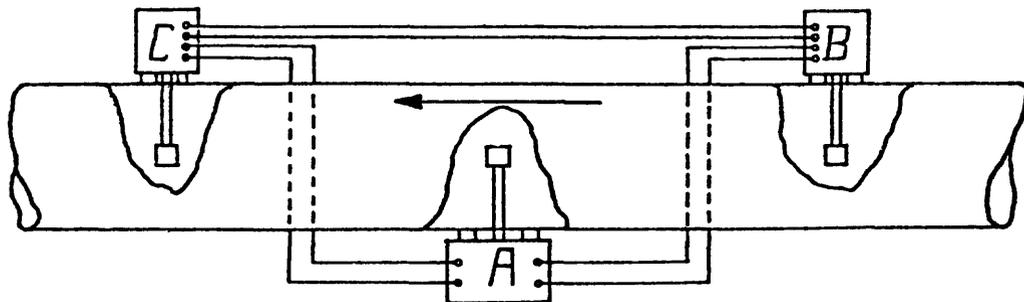


Figure 1. First AVM patent.

system. Soon ORE changed its philosophy and began to implement a system utilizing a minicomputer to manipulate the required timing and arithmetic functions. This system used an off-the-shelf Data General NOVA 1200 minicomputer and is basically the same system marketed today as their 7000 series. The software has progressed through a number of updates to provide more flexibility. The last generation of ORE equipment uses a microprocessor and is marketed as their 7200 and 7400 series.

Krupp began marketing Atlas-Flora equipment in 1972 as an outgrowth of its manufacture of depth-

sounding equipment. This equipment is generally second generation and uses integrated circuitry. The current equipment is the 10th revision of the original equipment design and is marketed as the Atlas-Flora 10 series.

AERE in Harwell, England, began producing an AVM system in 1974 under contract to the Water Research Center and Department of the Environment of the United Kingdom. The system, which can be considered second generation, is similar to the Westinghouse 204 and 601 series. The equipment is marketed in England by Plessey Radar, Ltd., and in the United States

by Redland Automation, Ltd., both under nonexclusive license by Harwell AERE.

Tokyo Keiki Co., Ltd., of Japan, one of the earliest manufacturers of open-channel AVM's, instrumented several sites in 1969. The equipment was marketed in the United States by Badger Meter Co. Tokyo Keiki has since concentrated on equipment to measure flow in pipes and small channels. These companies are no longer affiliated, and Badger now manufactures a series of pipe and small-channel AVM's of their own design.

Fokker Aircraft Industries, of Amsterdam, manufactures an AVM developed by the Institution of Applied Physics in cooperation with the Hydro-Instrumentation Department of Rijkswaterstaat of the Netherlands. Systems are marketed as the AKWA 76 series, which includes the use of a DEC PDP/11/03 minicomputer. The DEC minicomputer performs the same functions as the NOVA minicomputer of the ORE system. The basic difference in the systems lies in the acoustic circuitry. A fixed-gain preamplifier and transmitter is built into the Fokker transducer assembly and submerged with it. Other systems do not have preamplifiers or transmitters in their transducers.

Many more manufacturers produce systems that measure velocity and discharge over smaller distances, but they have not been included in this report.

BASIC PRINCIPLES

Two basic methods are used in the acoustic measurement of flow: (1) the time-of-travel method, where sound waves are transmitted along a diagonal in both directions relative to the fluid flow and traveltimes are measured in each direction, and (2) the Doppler shift method, where sound waves are projected along or diagonal to the flow path, and the frequency shift in the return signal (from backscattering of particles in the fluid) is measured.

For streamflow applications, time-of-travel equipment is more important in terms of basic capabilities and available systems.

Time-of-Travel Method

Acoustic measurement of fluid velocity is possible because the velocity of a sound pulse in moving water is the algebraic sum of the acoustic propagation rate and the component of water velocity parallel to the acoustic path. The mathematical relations shown are from papers by Smith (1969) and Smith and others (1971) and can be derived as follows (see fig. 2):

The traveltime of an acoustic pulse originating from a transducer at *A* and traveling in opposition to the flow of water along the path *A-C* can be expressed as:

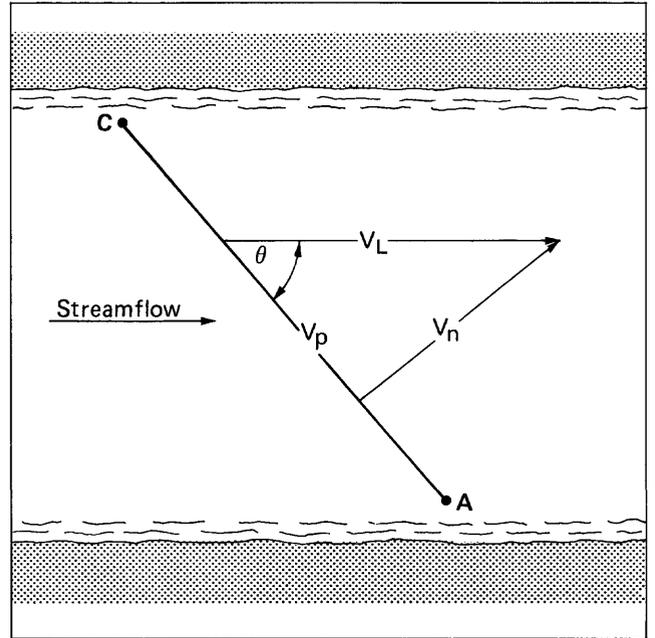


Figure 2. Velocity-component used in developing traveltime equations (Smith and others, 1971).

$$t_{AC} = \frac{B}{c - V_P} \quad (1)$$

and

$$c - V_P = \frac{B}{t_{AC}} \quad (2)$$

where

t_{AC} = traveltime from *A* to *C* (upstream path),
and
 c = propagation rate of sound in still water,
 B = length of the acoustic path from *A* to *C*,
 V_P = average component of water velocity
parallel to the acoustic path.

Similarly, the traveltime for a pulse traveling with the current from *C* to *A* (downstream path) is:

$$t_{CA} = \frac{B}{c + V_P} \quad (3)$$

and

$$c + V_P = \frac{B}{t_{CA}} \quad (4)$$

Using equations 2 and 4 and solving simultaneously for V_P ,

$$V_P = \frac{B}{2} \left[\frac{1}{t_{CA}} - \frac{1}{t_{AC}} \right] \quad (5)$$

and as

$$V_P = V_L \cos \theta \quad (6)$$

then

$$V_L = \frac{B}{2 \cos \theta} \left[\frac{1}{t_{CA}} - \frac{1}{t_{AC}} \right] \quad (7)$$

where

- V_L = line velocity (the average water velocity at the depth of the acoustic path), and
- θ = angle of departure between the streamline of flow and the acoustic path.

Note that the acoustic propagation rate (c) in equations 2 and 4 is canceled in equations 5 and 7 and is not a factor in computing water velocity. This feature makes use of equation 7 in conjunction with time-of-travel equipment valuable in computing water velocity in natural conditions. Fluctuations in the propagation rate owing to changes in water temperature and other density differences have no effect on the computation of water velocity.

Generally, three techniques are now used to determine upstream and downstream traveltimes: (1) Traveltime is obtained by directly measuring the time between the initiation of the transmit pulse and the first cycle of the received pulse, (2) pulse-repetition frequency is obtained by measuring the frequency of upstream and downstream pulse trains with respect to a given time interval, and (3) phase shift is measured by merging received transmissions of continuous signals. Another technique not yet widely used is to correlate the best received signal to the transmitted signal.

DIRECT TRAVELTIME

When a sonic transducer is triggered by a single spike of excitation voltage, it responds by emitting a burst of energy that oscillates at the frequency of the piezoelectric crystal encased in the transducer. This oscillation, shown in figure 3, rings for a period of time and is dampened by the physical constraints of the system. In direct traveltime measurement, the time between the start of the excitation pulse and the start of the receive pulse is measured. Normally, threshold detection of the first cycle of the arriving pulse is used to determine the start of the receive pulse. A variety of schemes has

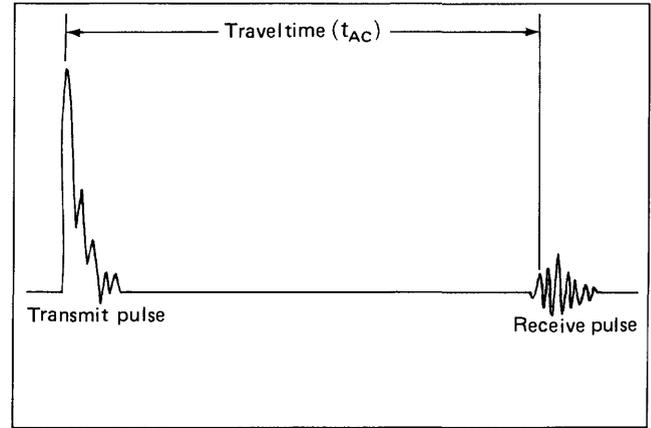


Figure 3. Voltage representation of transmit and receive pulses used with direct traveltime method.

been used to ensure that the proper signal, and not random noise (the normal background or static), activates the system timing. The simplest form of threshold detection is the triggering of a counter gate when the incoming pulse reaches a selected voltage level. Other schemes respond to two or more voltage levels occurring in one or more prescribed time intervals.

In threshold detection, only noise or noise spikes of the transmitter frequency are capable of triggering the system erroneously. If received signals are attenuated or distorted significantly (therefore not meeting the threshold criteria), the timing gate is not triggered. Some AVM systems have an automatic gain control to fix signal levels and eliminate data loss when signal strength is low. However, noise levels are also automatically increased, creating the possibility that the noise could trigger the timing gates. Secondary received pulses from reflection occur later in time and are of a magnitude that can trigger the timing gate if the direct pulse does not meet the threshold criteria. Most errors can be circumvented by electronic timing checks that limit the maximum anticipated traveltime and compare each traveltime with preceding transmissions. The application of these quality checks has become quite sophisticated.

PULSE-REPETITION FREQUENCY

In pulse-repetition frequency, the received pulse in each direction is used to trigger another transmit pulse, thus generating a train of pulses (first the upstream direction, then the downstream direction) whose period equals the total acoustic traveltime. This is commonly referred to as the sing-around method, and the combination of circuitry and transmission path in one direction constitutes a sing-around loop. From equations 1 and 3, frequencies and their repetition can be defined as follows:

$$f_{AC} = \frac{1}{t_{AC}} = \frac{c - V_P}{B} \quad (8)$$

and

$$f_{CA} = \frac{1}{t_{CA}} = \frac{c + V_P}{B} \quad (9)$$

where

f_{AC} = pulse transmission frequency in the downstream direction, and

f_{CA} = pulse transmission frequency in the upstream direction, then

$$rf = \left[\frac{1}{t_{CA}} - \frac{1}{t_{AC}} \right] = \frac{2V_P}{B} \quad (10)$$

where

rf = pulse repetition frequency.

Two drawbacks to this system are (1) the repetition frequency is normally small and the counting interval long, resulting in slow response time for the necessary resolution; and (2) reflected signals from previous transmissions tend to trigger the system at erroneous times. However, these problems have been successfully accommodated, and many AVM systems, particularly those used in pipelines, utilize this concept.

PHASE DETECTION

When sinusoidal signals of a given frequency are transmitted, the phase shift (time shift, not frequency shift) between upstream and downstream signals is

$$\phi = 2f(t_{CA} - t_{AC}) = \frac{4fBV_P}{c^2 - V_P^2} \quad (11)$$

Equation 11 (McShane, 1971) illustrates that the phase difference (ϕ) can be made larger and easier to measure by increasing the transducer frequency (f), which is generally an advantage.

The speed of sound is determined by measuring t_{AC} and t_{CA}

$$c = \frac{B}{2} \left[\frac{1}{t_{AC}} + \frac{1}{t_{CA}} \right] \quad (12)$$

and is achieved by sensing the start of the transmission

cycle and the start of the reception cycle in both upstream and downstream directions.

Sonic transducers can emit a continuous sinusoidal wave if driven by an oscillator. If two short-duration wave transmissions are emitted in upstream and downstream directions, their resulting received waveforms can be beat (superimposed) with an oscillator waveform whose frequency is near that used to drive the transmitter. In turn, the resultant waveforms can be superimposed, and the zero crossings will yield the time differential required for line-velocity measurement. The start of the reception cycle is determined by zero-voltage referencing of the modulated receive signal or aperture. Using the entire transmitted signal as a detector makes detection considerably less sensitive to noise but more susceptible to distortion from multipath interference. However, it is physically impractical to operate transducers for even short durations with as much voltage as is used by direct traveltime systems, so phase detection systems normally operate with less penetrating power.

CORRELATION COMPARISON

Sonic transducers can be driven to any frequency within a limited range of the resonant frequency of the piezoelectric crystal. Therefore, a sonic transducer is capable of emitting a frequency-modulated signal, and this signal can be modulated to create a pattern or "signature." This pattern can be digitized and placed in computer memory. The receiving transducer is activated at some calculated time after transmit and the reception digitized and stored. Sequential portions of the received data are then compared to the transmitted data by stepping through overlapping blocks of time. The best fit yields a maximum correlation function, and the time of the corresponding step number determines the traveltime. Another method to define a unique transmit pattern is by pulse conditioning techniques which emit a deformed pulse or "chirp."

A similar but simpler method tried by the Dutch (J. G. Drenthen, Rijkswaterstaat, oral commun., 1981) is to digitize time-voltage points of an anticipated receive signal from a single-burst transmission and correlate it with actual received data transmissions. Results show that this technique increases the reliability of attenuated signals but that it does not appreciably increase signal reliability where distortion exists. Correlation schemes are still in the experimental stage but show some promise in situations where appreciable signal attenuation and distortion occur. A modified signal will have the advantage of being identifiable in the noise level rather than having to exceed the noise level. Little or no filtering will be necessary and the dynamic range of the receiver will be increased.

Doppler-Shift Method

Motion of a scattering object will change the frequency of a returned signal. The frequency of sound observed (scattered) from an object moving in a path directly away from the source is

$$f_o = f_s(c - V_o)/c \quad (13)$$

where

- f_o = the observed frequency,
- f_s = the source frequency,
- V_o = the velocity of the object, and
- c = the velocity of sound.

From the point of view of a fixed receiver at the source location, the scattering object becomes a moving source and the frequency (f_r) at the receiver is

$$f_r = f_s \frac{(c - V_o)}{c + V_o} \quad (14)$$

Measurement of the Doppler frequency shift versus time provides a means of determining the velocity of the water mass versus distance along the transducer beam (fig. 4). By assuming that the scatters are moving with the velocity of the water, the frequency data and range is converted to water velocity versus transverse distance across the river. Ranging is done by allowing designated time intervals to listen for backscattering frequencies. Velocity of sound (designated time intervals) is adjusted by a reference backscatter at a known distance.

Doppler equipment can measure stream velocity provided sufficient particles or air bubbles are suspended in the streamflow to backscatter the signal. The lower threshold is not known. Doppler equipment, capable of measuring velocity at remote points using only one transducer, can be an excellent system for many applications of fluid-flow measurement. However, the Doppler method lacks the penetration capabilities of time-of-

travel equipment because it has greater susceptibility to interference from boundary conditions (bottom and surface reflections), and is subject to signal attenuation from the same particles necessary in backscattering the signal. In contrast with time-of-travel systems, Doppler systems operate with a larger statistical scatter from individual measurements of shift, and require a great many more samples to obtain reliable results.

LIMITING CRITERIA

Four basic phenomena that affect the performance of acoustical equipment in measuring streams are (1) the multipath phenomenon that is dependent on cross-section geometry, (2) the ray-bending phenomenon caused by temperature or conductivity gradients, (3) the signal-attenuation phenomenon caused by sediment and entrained air, and (4) variable streamline orientation or large eddy flows.

Multipath Phenomena

Lowell (1977) has postulated that a reflected signal that arrives at a receiver within one wavelength of the direct signal will cancel the first pulse of the signal (fig. 5). Therefore, this phenomenon is a limiting criterion for locating transducers based on cross-section geometry and the clearance height in figure 5 is the minimum height needed to avoid multipath problems. Table 1 gives some typical statistics for frequencies generally used in streamflow applications.

Accuracy of AVM systems depend on the precision with which the individual traveltimes can be measured. Errors in indicated velocities are a linear function of timing error in either direction. Table 1 shows errors that could result if timing in one direction were triggered by the first pulse of the receive signal and timing in the other direction was triggered by the second pulse of the receive

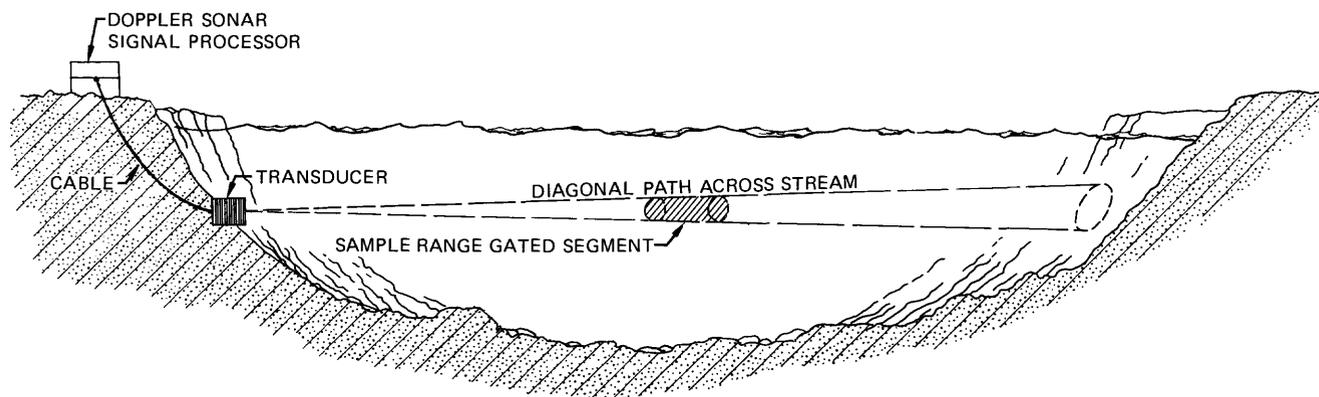


Figure 4. Doppler-ranging technique (AMETEK, 1979).

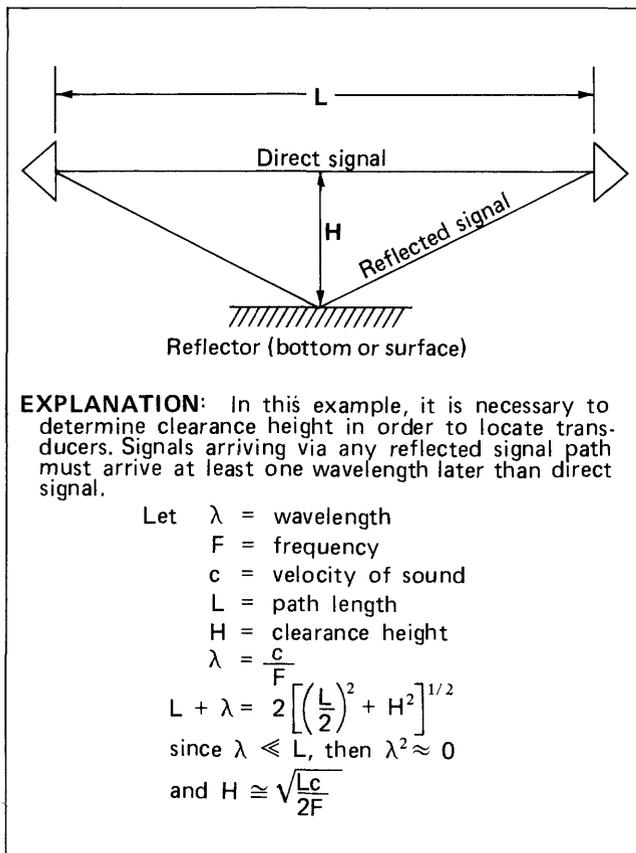


Figure 5. Multipath interference (modified from Lowell, 1977).

Table 1. Typical path length versus operating frequency, clearance height, and effects of one carrier-cycle timing error [For clearance height, see figure 5]

Path length (meters)	Operating frequency (kHz)	Clearance height (meters)	Velocity error for one carrier-cycle timing error (meters per second)
500-1,000	30	3.5 -5.0	-- --
200- 500	100	1.2 -1.9	0.011-0.004
50- 200	200	0.43-0.87	0.136-0.054
20- 50	300	0.22-0.35	0.230-0.090
5- 20	500	0.09-0.17	0.542-0.145
1- 5	1,000	0.03-0.06	2.67 -0.267

signal, a phenomenon that could occur when signals are drastically attenuated.

Ray-Bending Phenomena

The velocity of sound in water is affected by density changes produced by temperature or salinity gradients. Figure 6 shows how the velocity of sound changes with

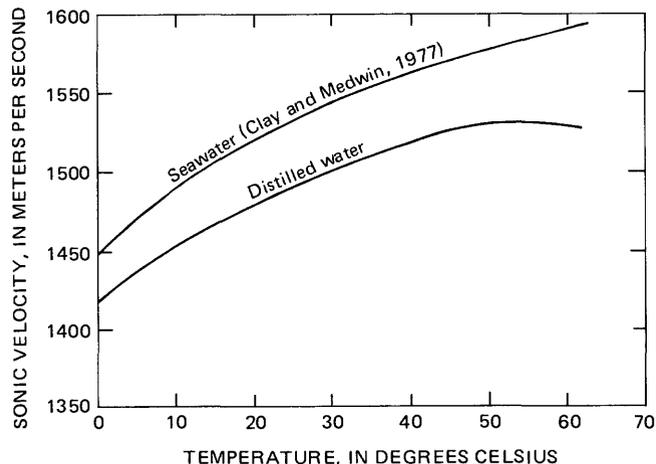


Figure 6. Sonic velocity in water.

temperature for distilled water and seawater (salinity = 35 g/L). Consequently, ray bending, as illustrated in figure 7, will occur in the presence of either vertical or horizontal density gradients.

Temperature gradients of 0.1°C per meter or more generally occur in the top one-half meter of a stream cross section in slow moving and ponded water. Below this one-half-meter depth, temperature gradients are normally much less than 0.1°C per meter. Data in an unpublished report by E. J. Jones (Geological Survey, Sacramento, Calif., Subdistrict) show that out of 183 temperature traverses (24 sites with 15 to 30 observations per site), only five had temperature differences exceeding 0.5°C. Temperature variations at most sites were normally too small to measure on the thermistor-type thermometer that was used. The maximum temperature differential was 4°C, which occurred in summer in a small stream with ponded water. The above data suggest that temperature gradients probably will be of little concern where water is moving, except at sites downstream from tributary flows with a different temperature than that of the main stem or at sites in or near estuaries subject to flow reversal and incomplete mixing with seawater of a different temperature.

Figure 8 is a plot of beam deflection versus temperature gradients caused by ray bending based on Snell's law (Clay and Medwin, 1977). For example, if a maximum vertical temperature gradient of 0.1°C per meter can be expected in a stream where a path of 200 m is to be measured, then the maximum signal strength would miss the receiving transducer by 4 m, but a usable signal would be received from the periphery of the 5° cone of transmission (5° beam width). Given this same temperature gradient and a path of 500 m, the maximum signal strength would be deflected 24 m and no usable signal would be received for a 5° beam width transducer. Temperature gradients are normally nonlinear and the maxi-

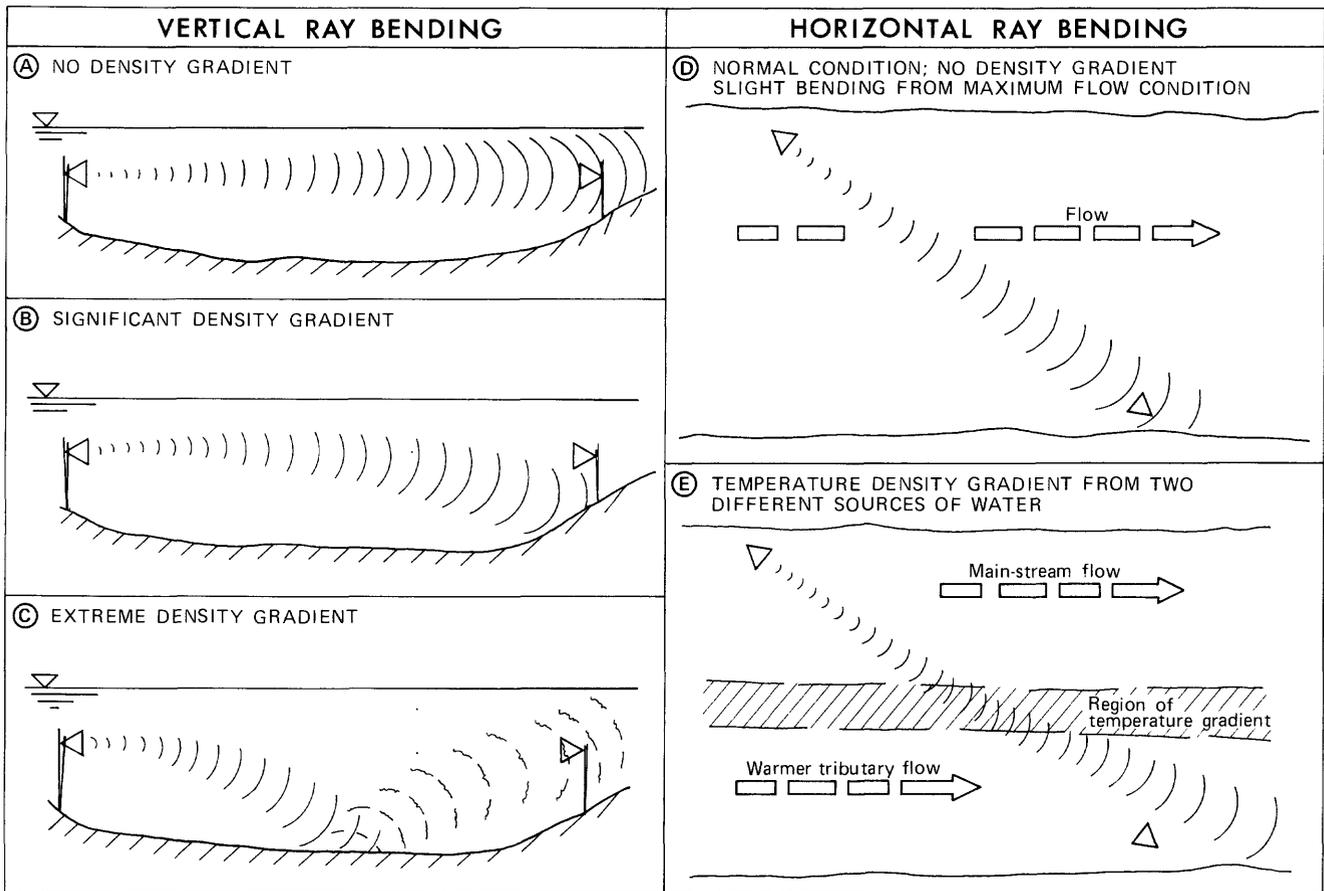


Figure 7. Signal bending caused by different density gradients.

imum gradient generally occurs in the top one-half meter of water depth. If transducers are located below this depth, then linear assumptions are good. In defining temperature gradients in the horizontal, it is important to define the area affected by the differential because the smaller the distance, the greater the gradient. Signals can actually be reflected by thermal layers of water. Horizontal gradients may occur even more frequently than vertical gradients.

Salinity (specific conductance) gradients occur routinely in estuaries affected by tidal action. In contrast to temperature, these gradients are sometimes so large that proper acoustic transmission cannot occur. Where thermal or salinity problems are expected, experience to date suggests the necessity for a detailed onsite investigation. Figure 9 shows the plot of conductivity gradients versus beam deflection and can be used in the same manner as in figure 8.

The increase in path length as a result of bending is normally very small; however, the differences in sampled velocity may be large and can create significant error. Where signal paths are very long and ray bending in the vertical causes signal reflection from bottom and (or) surface (and possibly again and again), error due to in-

creased path length and sampled velocity becomes much greater. Because multiple bounces can cause multipath interference, use of presently available AVM equipment should be avoided at sites where multiple bounces may occur.

Signal-Attenuation Phenomena

Acoustic signals are attenuated by absorption, spreading, and scattering. Attenuation or signal losses from these sources have to be added together to determine if the received signal strength will be adequate to be usable in an AVM system. Attenuation is measured in nepers (n) or decibels (dB). The decibel is a ratio of the observed sound pressure (ρ_o) to the pressure level of the source (ρ_s). This can be expressed in the form

$$1 \text{ dB} = 20 \log \frac{\rho_o}{\rho_s} \quad (15)$$

Voltage can be used interchangeably with pressure if both source and observation points have identical impedances. Nepers is also defined as a power ratio and is

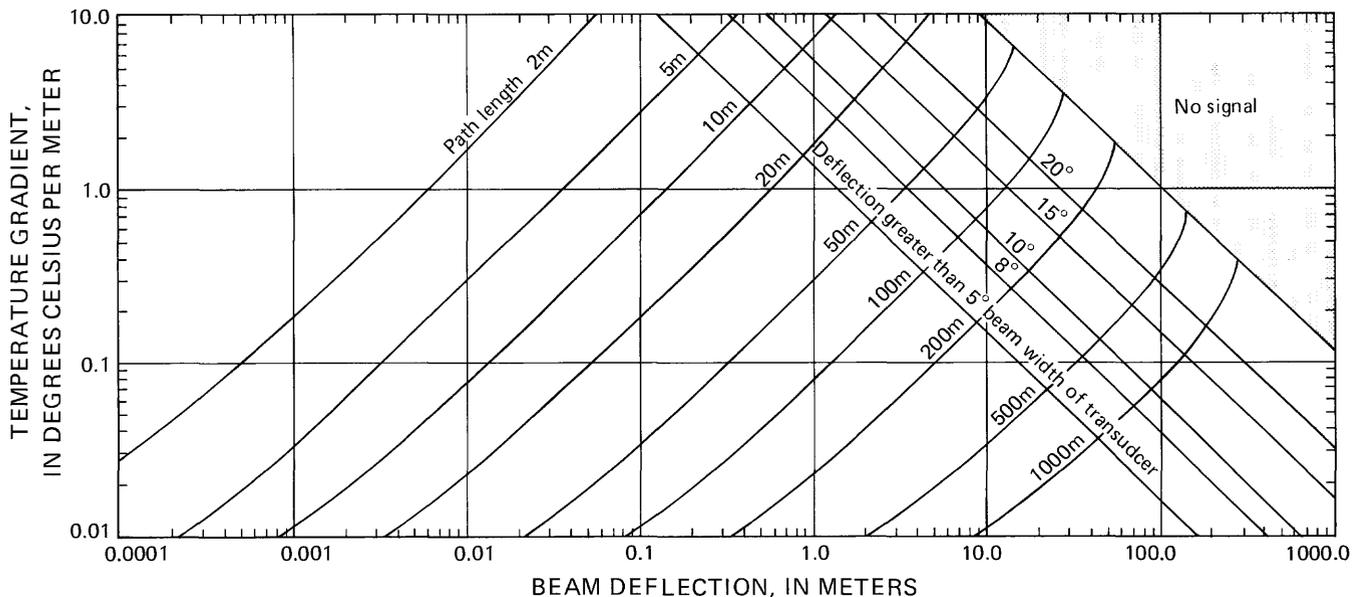


Figure 8. Beam deflection from linear-temperature gradients for different path lengths. Transducer directivity or beam width determined at the 30-dB level of the transmitted signal pattern. The signal is propagated beyond the beam width but at a weak level. In the shaded area the deflection is so great that signals cannot be received directly for any transducer beam width.

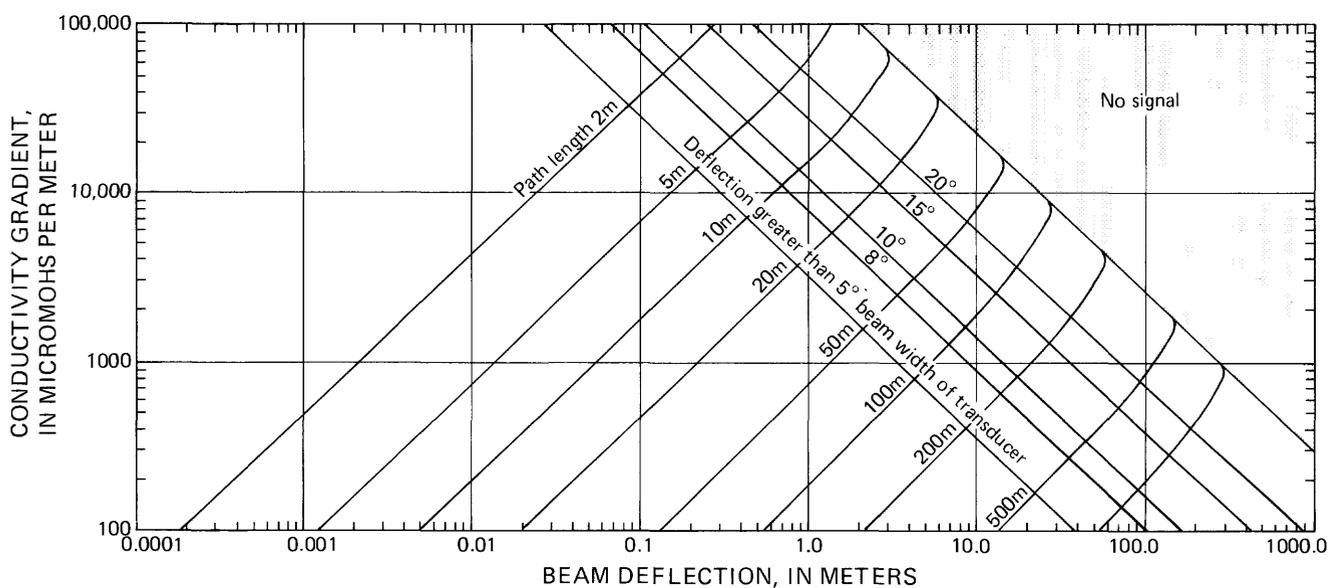


Figure 9. Beam deflection from linear-conductivity gradients for different path lengths. Transducer directivity or beam width determined at the 30-dB level of the transmitted signal pattern. The signal is propagated beyond the beam width but at a weak level. In the shaded area the deflection is so great that signals cannot be received directly for any transducer beam width.

most commonly used with metric distances. To convert decibels to nepers, multiply by 0.1151.

Absorption involves the conversion of acoustical energy into heat. In distilled water, absorption is affected by frequency. In seawater, absorption is additionally affected by the energy consumed in the ionic relaxation of magnesium sulfate ($MgSO_4$). Figure 10 shows the relation of attenuation to seawater and to distilled water.

Spreading loss is a geometrical effect caused by the

regular weakening of a signal as it spreads outward from the source. It varies with distance according to the logarithm of the path length (Urlick, 1975) and is expressed in metric units as follows:

$$\alpha = 2.033 \log (1.094L) \quad (16)$$

where

α = attenuation, in nepers, and
 L = the path length, in meters.

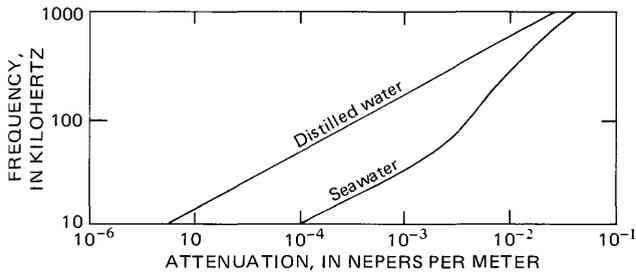


Figure 10. Attenuation caused by absorption.

Scattering losses are caused by suspended sediment and entrained air which absorb sound as well as reflect or scatter it. Scattering losses normally predominate because

of sediment particle sizes commonly found in streams and signal frequencies generally used in AVM systems. Figure 11 shows attenuation related to particle diameter for specified frequencies. These curves are developed from equations by Urick (1975) and have not been experimentally verified for the frequency range in which AVM's normally operate. Experience with existing AVM's suggests that attenuation obtained from Urick's equations is generally higher than actually occurs. These curves also indicate that particle-size distribution is important in computing attenuation.

A gas bubble of the same diameter as a sediment particle can attenuate the signal 400 times more than a particle if the bubble resonates (Clay and Medwin, 1977).

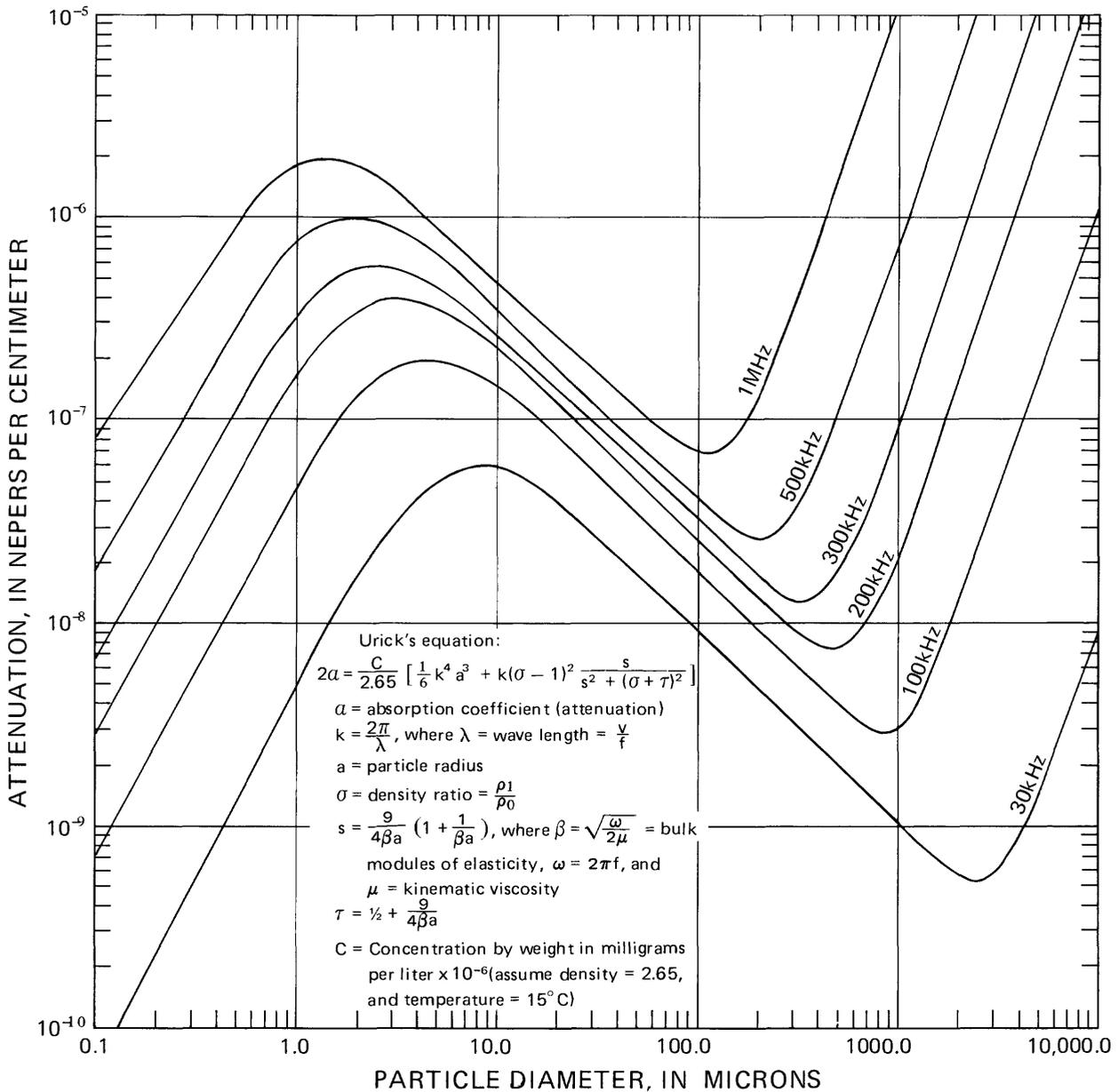


Figure 11. Attenuation from sediment for selected frequencies for a sediment concentration of 1mg/L. To determine total attenuation from sediment, results must be weighted by particle size and then multiplied by concentration.

Resonance occurs when the bubble is approximately the same diameter as the signal wavelength. Little is known about bubble populations in streams; therefore, attenuation caused by bubbles cannot always be predicted. Observations, using portable acoustic equipment below Grand Coulee Dam, showed signal attenuation from entrained air in the channel for distances of 5 to 8 km below the dam. Data were collected when 7,000 m³/s was being spilled. Using an estimated 3 m/s mean velocity, the observations imply a bubble persistence of 25 to 45 minutes after water was spilled. Onsite measurements of signal attenuation should be made at critical times at sites where bubbles from air entrainment could cause problems.

Variable Streamline Orientation

Streamlines of flow in a cross section may change direction with time and discharge (see fig. 12). AVM systems normally have transducers located near each bank on a diagonal across the stream. When streamlines of flow change direction, an error in angularity is introduced. Table 2 shows ratios necessary to adjust for changes in angularity. A crossed path (as shown in figure 12) can provide valuable information for making necessary corrections. Differences in cross-sectional area along

the two acoustic paths introduce errors to the computed discharge (approximately 1 percent error for 20 percent difference between cross-sectional areas). Neither single-path nor cross-path methods can be used to compute velocity if large eddies persist in the stream. Stream reaches with large eddies should always be avoided when locating an AVM.

SYSTEM CONSIDERATIONS

The U.S. Geological Survey operates and maintains six AVM's. Considering the use of acoustic measurement in other applications today, this relatively small number of operational systems seems out of step. Because AVM systems have been expensive and sophisticated, they have not been considered for use in stream gaging. Costs of the initial instrumentation, mounting of transducers, laying of a submarine cable, construction of an air-conditioned and heated building, and continuous maintenance of complex equipment have discouraged many potential users.

An evaluation of the performance, required maintenance, calibration techniques, and equipment accuracy is necessary to determine what has been learned from the first generations of operational equipment.

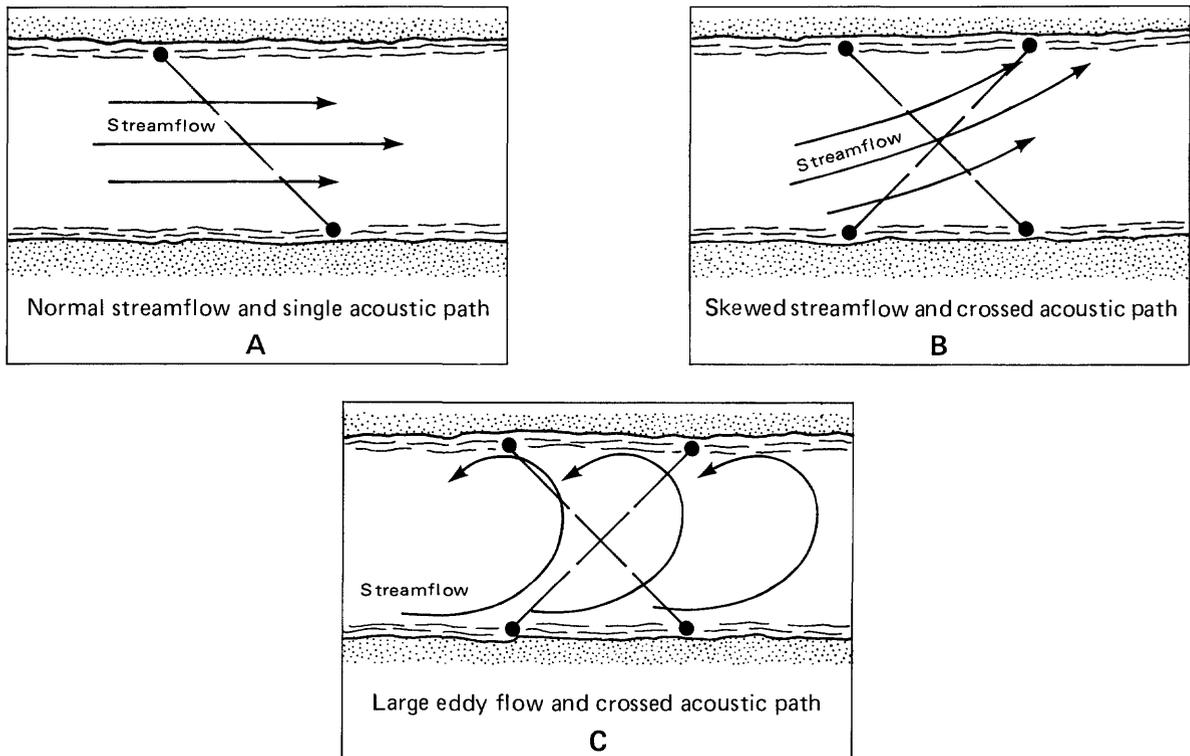


Figure 12. Schematics of angularity and eddy flow. Schematic A shows that only a diagonal path is necessary when streamlines of flow are unchanging. When streamlines change as in schematic B an error in angularity is introduced and a crossed acoustical path must be used to detect the change. If a large eddy affects all or part of the flow in the section as shown in schematic C then a cross path is inadequate. Stream reaches with large eddies should be avoided in AVM location.

Table 2. Adjustment factors to velocity for error path angle
[For report by Smith and others, 1971]

Path angle θ	Error								
	-4°	-3°	-2°	-1°	-0°	+1°	+2°	+3°	+4°
30°	1.040	1.030	1.020	1.010	1.000	0.990	0.989	0.970	0.960
40°	1.070	1.052	1.035	1.017	1.000	.983	.965	.948	.930
50°	1.083	1.062	1.042	1.021	1.000	.979	.958	.938	.917
60°	1.121	1.091	1.060	1.030	1.000	.970	.940	.909	.879

Minicomputer System

The AVM systems used by the Geological Survey (fig. 13), incorporate a direct travelttime mode of operation. Receive signals are detected by a double voltage threshold. A common transceiver is used to minimize differentials imposed by the electronics that might bias timing functions in either direction. The basic control of the system, all arithmetic functions, and formulation of data

output are done by a minicomputer. Because the function of this central processor can be modified by software changes, a variety of operating and debugging routines can be selected. Onsite selection of sampling intervals, averaging intervals, and quality checks are possible because programing is flexible. Conversion of output from velocity index to discharge can be made by the entry of desired constants of path length, path angle, velocity adjustments, and area adjustments on the teletype keyboard.

Systems are programed to make acoustic transmissions once in each direction every 4 to 10 seconds, to provide a readout of average path velocities and discharge once every 10 minutes, and to compute hourly and daily averages. Data not meeting quality timing checks are flagged as questionable. No significant equipment modifications have been made since the initial installation of all systems. On several occasions, computer programs have been updated to remedy faulty logic and to provide more flexibility.

Calibration of Operational Systems

All but one of the AVM systems maintained by the Geological Survey are single path and have been calibrated by current-meter measurements in order to compute a record of discharge. Basic data recorded are stage (H) and average velocity parallel to the acoustic path (V_P). These parameters are correlated with the geometric and hydraulic conditions at the site in order to define the elements of the basic-flow equation:

$$Q = A \bar{V} \tag{17}$$

where

- Q = the discharge,
- A = the area of the cross section, and
- \bar{V} = the mean velocity in the cross section.

The relation between area (A) and stage (H), in most cases, can be adequately defined by a second-order equation:



Figure 13. Minicomputer and teletype of Columbia River at The Dalles, Oreg.

$$A = C_1 + C_2H + C_3H^2 \quad (18)$$

where

C_1 , C_2 , and C_3 = constants that can be evaluated from data obtained during conventional current-meter measurements.

The relation between the path velocity (V_p) and the mean velocity in the cross section can also be represented by a second-order equation:

$$K = \frac{\bar{V}}{V_p} = C_4 + C_5H + C_6H^2 \quad (19)$$

where

K = a ratio (that may or may not include the path angle), and

C_4 , C_5 , and C_6 = constants evaluated from current-meter measurements and corresponding AVM path velocities.

Substitution of equations 18 and 19 into equation 17 results in the general equation:

$$Q = (C_1 + C_2H + C_3H^2)(C_4 + C_5H + C_6H^2)V_p \quad (20)$$

Equation 20 can be combined further into a fourth-order equation with five constants, which is done in some programs utilized by USGS systems, but the concepts of rating analysis are simplified if this equation is left in the form shown. This permits separate analysis of area versus stage and K versus stage relations.

Accuracy of Operational Systems

Figures 14 and 15 are respective plots of area versus stage and K versus stage relations for Columbia River at The Dalles, Ore. The K values in figure 15 represent a ratio of mean velocity to an index of velocity. The number produced by the original AVM equipment was dimensionless, and not scaled to represent V_p . Accuracy of the area versus stage curve is excellent, and the demonstrated stability of the K versus stage curve is also impressive. The standard deviation of departures for the stage-area relation is 0.7 percent and for the stage- K relation is 2.7 percent. Only one out of 60 measurements made from 1969 to 1976 lies outside the ± 5 percent error range. Combination of these error sources indicates a probable accuracy of 2.8 percent for computed discharges. When most flow is through the turbines at The Dalles Dam, comparison of discharges computed independently from operation logs from the dam substantiates this estimate of probable accuracy. Rating information plotted in figures 14 and 15 represents 7 years of

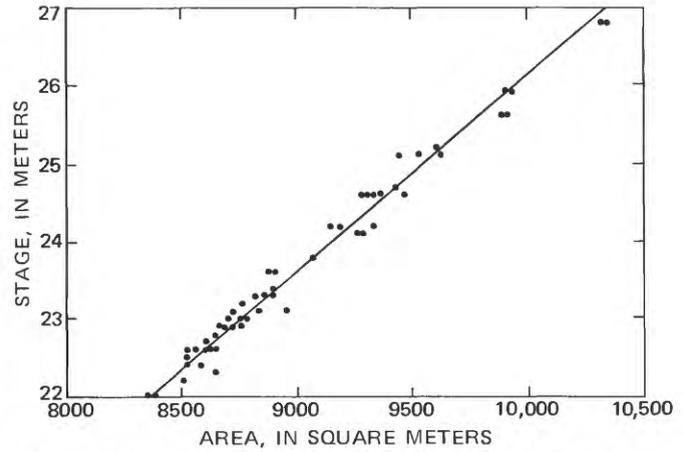


Figure 14. Relation of stage versus area for Columbia River at The Dalles, Ore. Points represent measurement of area by sounding.

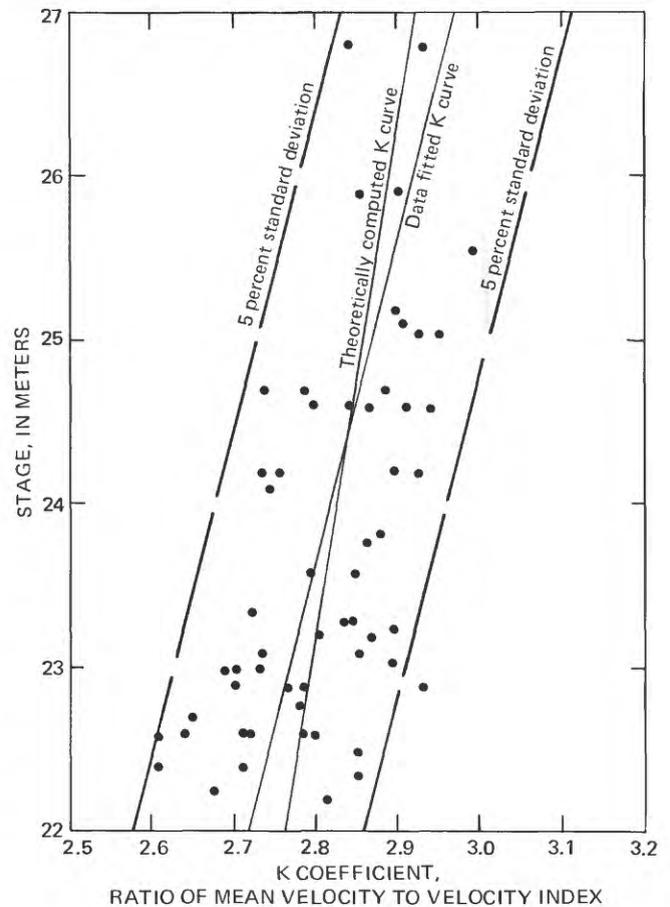


Figure 15. Relation of K versus stage for Columbia River at The Dalles, Ore. Points represent the ratio of average measured velocity to the velocity index of the AVM system.

operation. The ratings were developed in 1970, and were not significantly modified until new equipment was installed in 1978. This fact is emphasized because it proves the long-term stability of the system and supports the

concept that AVM's are dependable tools for stream gaging.

Statistics pertaining to accuracy have been equally encouraging at the other AVM locations. For 25 current-meter measurements made at Snake River at Lower Granite Dam, the area-related standard deviation was 1.3 percent and the K deviation 3.3 percent. For Willamette River at Portland, where 44 current-meter measurements were made, the area deviation was 1.6 percent and the K deviation 3.0 percent. The Willamette River relation for K has been changed five times; however, none of the changes has resulted in more than a ± 5 percent change in discharge. Incidentally, the Willamette site is the only AVM site mentioned that does not measure across the entire stream cross section. For 26 measurements made at Grand Coulee Dam, the standard deviation was 3.6 percent for discharge (combined error of K versus area and K versus velocity). For 43 measurements made at the Sacramento River, the standard deviation was 2.3 percent for discharge.

Line-velocity measurement accuracy is limited by the resolvable difference in sound speed between upstream and downstream traveltimes. Determination of these traveltimes in an AVM system is normally accomplished by a voltage-threshold detector. The frequency of the system, the allowable attenuation of the signal (for some systems), the tolerance of the threshold detector, and the path length, determine system resolution. For systems used in streamflow measurement, resolution is normally within 0.01 m/s. AVM systems can monitor flows at velocities less than the threshold level for mechanical or head-loss meters (0.1 m/s).

Theoretical Calculations

An independent theoretical K curve was developed for all sites. K values were calculated for a range of stages based on cross-section data and assuming parabolic vertical-velocity distribution. Figure 15 shows this theoretical K curve for Columbia River at The Dalles. For all sites, statistical scatter of streamflow measurements about the theoretical curve was not significantly larger than the scatter about the regressed curve. A recent study by the Dutch (Drenthen, 1981) indicates similar results. The statistical study by the Dutch was based on logarithmic velocity distribution for a wide variety of cross section and boundary situations, and showed an expected accuracy of about 6 percent for measurements based on one line velocity (refer to table 3). Four paths seem to be the optimum number necessary to define velocity for most situations, and this would result in a probable 2 percent accuracy.

For many locations of AVM systems in large streams, current-meter measurements may be unneces-

sary if accurate path length, path angle, and cross-section data are available. However, the true path angle is difficult to obtain, and an error of $\pm 1^\circ$ (for path angles of approximately 45°) will yield a velocity error of ± 1.7 percent (see table 2). A current-meter measurement or the use of another acoustical path crossing the existing path is necessary to verify path angles. Path lengths which can be easily measured by conventional techniques, yield an error of ± 0.2 percent for a 500-meter path.

Maintenance Requirements

Minicomputer-based AVM systems are sophisticated electronic devices that require maintenance by competent technicians. The technician must be knowledgeable in diagnostic troubleshooting and in the operation of oscilloscopes, teletypes, and computers. System failures can result from problems in input-output devices (including radio telemetry), minicomputer programing and electronics, cable breakage, power supplies, and from many other seemingly minor items. In recent years, periodic contract maintenance provided by the manufacturer has improved overall performance. The best performance of AVM systems has been achieved at sites monitored by telemetry that indicates outages immediately so that service can be scheduled accordingly. Sites visited infrequently have significant downtime.

To date, most equipment malfunctions have been traceable to teletype or minicomputer failures. If the teletype is serviced at regular intervals by qualified personnel and the minicomputer is kept in a temperature-and dust-controlled environment, the AVM systems now used should operate relatively trouble free.

A good spare-parts inventory is also essential to minimize equipment downtime. Districts in the Northwest maintain a transportable spare-parts package that can be shipped to any of the four AVM sites within hours by common carrier.

Significant problems have been encountered with the initial installation of AVM systems. Although systems can be installed and placed in operation by competent technicians, experienced personnel should be on hand to determine if the system is operating at peak performance.

OPERATIONAL STREAM GAGES

Columbia River at the Dalles

An AVM was first placed in operation on the Columbia River at The Dalles, Oreg., in January 1968 (see report by Smith and others, 1971). A traveltime-difference method and single-threshold detection technique were used in this system. Transducers were placed at each

Table 3. Error analysis for mean velocity in a cross section based on equations using the velocity along a horizontal path [Modified from Drenthen, 1981]

Number of paths	Equations ¹	Error (percent)
1	$\bar{V} = 0.96V_{P0.5}$	6
2	$\bar{V} = 0.50(V_{P0.2} + V_{P0.8})$	4.5
3	$\bar{V} = 0.40V_{P0.8} + 0.30V_{P0.4} + 0.25V_{P0.2}$	3.5
4	$\bar{V} = 0.25(V_{P0.8} + V_{P0.6} + V_{P0.3} + V_{P0.1})$	2.0
6	$\bar{V} = 0.10V_{P0.0} + 0.20V_{P0.8} + 0.20V_{P0.6} + 0.20V_{P0.4} + 0.20V_{P0.2} + 0.10V_{P0.2}$	2.0

¹ V_p denotes fraction of total depth.

end of a 552-meter path at an elevation of about 18.3 m, approximately 4.6 m below normal pool elevation. An abandoned telephone cable was used as a submarine link between transducers. Initial performance was good, but the system began to malfunction in April 1968. System failure was apparently related to changes in river environment and the effects of these changes on the propagation of acoustic signals.

Transducer realignment and circuitry modifications resulted in minor improvement, but frequent periods of poor record persisted. An extensive field surveillance was made by Westinghouse field engineers in January 1969. They concluded that the loss of signal was due to signal bending in response to very small thermal gradients near the surface of the river. Correlation between system outages, low flow, and cold weather lent some support to this theory. The recommendation of the Westinghouse engineers was to lower the transducers and shorten the path length. They theorized that significant temperature gradients would less likely be found near middepth in the cross section and that shortening the path length would provide further security against signal loss.

Relocation of transducers, which lowered the acoustic path to an elevation of 11.6 m and shortened it to a length of 402 m, was completed in April 1969. After final system modifications and tuneup that same month, a very stable operating system emerged. As a result, signal outages of more than an hour were infrequent, and record loss from all causes averaged less than 3 percent from 1969 through 1975.

During 1976 and 1977, record loss became more frequent due to deterioration of certain electronic parts, especially the peripheral output circuitry. In 1977, agencies involved purchased new instrumentation to replace the old, thus increasing versatility and providing the capability of interfacing with other systems. The replaced acoustic transmitters and receivers of the original equip-

ment had operated almost flawlessly from 1967 to 1977 and would probably still be operating had not the processor and peripheral equipment circuitry become faulty and obsolete.

By 1978, the submarine cable in use since 1967 deteriorated to the point where its signal-carrying capacity was tenuous at best. Noise levels increased with time, as did the data loss; however, even with the extreme noise problem, the equipment operated with only 10 percent loss of data. In April 1981, the old cable was replaced with an armored coaxial cable which eliminated much of the noise problem and increased the dynamic range of the system.

Snake River at Lower Granite Dam

AVM equipment was placed in operation in October 1972, with transducers placed 5.2 m below normal pool elevation at a path length of 320 m. Until 1975, velocity data collected at this site were relatively complete except for two short periods in January and June of 1974. Presumably, signal loss for these short periods could have been from high concentrations of suspended sediment during the high flow in the river, additional entrained air due to increased turbulence, and (or) the noise that was generated by movement of the cobblestone bed material.

In February 1975, Lower Granite Dam became operational and subsequently operation of the AVM became intermittent. Spill over the dam caused continuous air entrainment initially, but installation of turbines reduced spill and resulted in less turbulence. From 1975 to 1976, flow pattern from spillways changed and the decreased spill increased the reliability of the AVM system. Currently 85 percent of the data is normally unflagged (noted as erroneous by the system) and immedi-

ately acceptable when electronic circuitry is functioning. However, the equipment has had about 30 percent downtime because of electronic malfunctions in power supplies, computer circuitry, and teletype components.

Columbia River Below Grand Coulee Dam

AVM equipment was placed in operation in October 1972, with transducers placed 5.8 m below normal pool elevation and with a path length of 205 m. This system produces a 10-minute average of reservoir outflow that assists the U.S. Bureau of Reclamation with operational control of Grand Coulee Dam.

Initially AVM operation was sporadic. The AVM was placed 1.4 km downstream from the dam to provide a real-time operating record that would be little affected by in-channel storage. The system operated only during those periods when all, or nearly all, the flow passed through the powerplant. Large quantities of air were entrained in the water during periods of spill, causing the attenuation of acoustic signals and loss of data.

Acoustic-transmission problems associated with water turbulence and air entrainment were alleviated by the increased use of the third powerplant which began partial operation in September 1975. For the years 1976, 1977, and 1978, the appraisal of AVM operation indicated that 75, 84, and 94 percent of the data, respectively, was unflagged and immediately acceptable. The increase in acceptable data correlates with the addition of each new turbine put in operation.

The instrumentation has had its share of electronic malfunctions. Earth-moving activities and heavy construction nearby caused a very dusty environment inside the instrument shelter. When construction activities ceased, so did most of the electronic problems. Excellent cooperation and assistance from U.S. Bureau of Reclamation personnel, who are in the vicinity at all times, have been helpful in maintaining a high level of performance and minimal downtime for this equipment.

Willamette River at Portland

AVM equipment was placed in operation November 1972, and is in one of the towers of the Morrison Street Bridge. Transducers were placed at an elevation of 3.9 m below mean low water. One transducer was located on the pier of the bridge drawspan and the other on the seawall next to the bridge. The path length of 226 m is about two-thirds of the total channel width. During low-flow periods there is reverse flow from tidal fluctuations.

When this system is in operation, approximately 95 percent of the data is unflagged and immediately acceptable; however, there has been considerable downtime be-

cause of ships docked in the acoustic path. In 1977, a ship damaged one of the transducers by knocking it from its mount. In February 1978, this problem was resolved by lowering the seawall transducer 2.4 m and protecting it with a shield directly above the mounting.

The submarine cable link used for the Willamette River system is very noisy but adequate for high-quality system performance. The control cable used for electro-mechanical functions of the bridge carries the transmit and receive signals on a previously unused pair of conductors. Other conductors used in this cable carry 60-cycle AC and motor-control signals that induce noise in the pair of conductors used to carry AVM signals. Fortunately, no signals are present with frequency characteristics similar to operating frequency of the AVM system.

Sacramento River at Freeport

AVM equipment was placed in operation November 1978, with transducers placed 2.93 m below summer pool elevation and a path length of 196 m. The AVM produces an hourly average of discharge that assists the county of Sacramento in controlling effluent from the regional waste-water treatment plant. The plant outfall is approximately 79 m downstream from the midpoint of the transducer cross section. A high degree of accuracy and dependability of flow measurement must be maintained, especially during periods of low flow.

Performance of this system has been excellent, with only 10 percent data loss from November 1978 to October 1980. Most record loss was caused by electrical noise. A nearby faulty powerline insulator seemed to have been the cause of this noise, and therefore has been replaced. During the problem period, the receiver gain had been set lower than normal to keep noise below detector threshold levels.

The calibration of this system has been extremely stable, as evidenced by the fact that a single rating fits all 43 measurements made to within +2.5 to -8.8 percent, with a standard departure of 2.3 percent.

Osage River Below Truman Dam

AVM equipment was placed in operation in May 1978, with six transducer paths. The transducer pairs are set 1.5, 3.0, 4.2, 6.0, 7.6, and 8.5 m below mean low water. The streambed is at an average elevation of 9.4 m below mean low water. Path lengths range from 200 to 284 m. The system will provide a record to assist the Army Corps of Engineers with the operational control of Truman Dam. The installation is 600 m downstream from the dam.

To date, performance of the AVM at this site has been very poor. Significant loss of record is attributed to the flow characteristics of the channel and the presence of bubbles in the water. Construction at Truman Dam has not yet been completed, and all water flowing past the AVM has passed over the spillway, entering the channel at an angle and on one side of the stream. Large eddies are produced just below the dam and pass through the measuring section, causing the streamlines to cross the acoustic path at variable angles. Consequently, the AVM can register apparent flows that range from -85 to 285 m³/s for constant downstream flow of 140 m³/s. None of the acoustic paths in use is a cross-path; however, because of the very unstable hydraulic conditions, there is no reason to assume that the errors are random and compensating.

In addition to the undefined-streamline orientation problem, gas bubbles attenuate the acoustic signals below threshold levels. The bubble source is from the production of methane gas by large amounts of decaying organic matter recently submerged during filling of the reservoir.

In addition to the problems above, much damage to the electronic system has been caused by lightning, faulty wiring in the shelter, extremely high-supply voltages, and rats and mice gnawing transducer cables. All the electrical problems have now been resolved. When the hydraulic conditions in the channel are corrected and the powerhouse goes on line in the fall of 1981, it is anticipated that usable real-time data will be obtained.

Operational Gages in the United Kingdom

Nineteen AVM systems are presently in operation in the United Kingdom (Childs, 1980). Locations of these systems can be found in table 4 (at the back of this report). Two of the systems are multipath and one is a portable system. With satisfactory conditions and efficient operation, the English single-path systems yield a ± 5 percent accuracy. Systems with at least four paths have shown accuracies within ± 1 percent.

Problems regarding AVM operation in the United Kingdom have been varied and numerous; however, the ultrasonic circuitry by itself has been relatively trouble free. The more serious and frequent faults have generally occurred with the peripheral equipment such as paper-tape punches, the depth gage and interface, and the transmitter-receiver switching circuitry. Record loss has also occurred because of changes in the acoustic environment. Extreme temperature gradients and heavy weed growth have perpetuated signal loss at a number of installations. Attempts to discourage weed growth by lining the channel with a polythene cover have been moderately successful.

Velocity and stage data from the English AVM installations are processed in a main-frame computer by their Water Data Unit. Because punch-tape recorders generally operated poorly, processing data was lengthy, and considerable data were lost or unusable.

The English recognize that hydrological instrumentation and data acquisition systems have and will become more sophisticated, and it is necessary to augment their electronic expertise and develop sound programmed maintenance. English maintenance philosophy consists of three basic items, (1) a scheduled maintenance, (2) an adequate technical manual, and (3) a good spare-parts inventory. They feel it is desirable to have weekly checks by a hydrometric technician and quarterly checks by a qualified electronics engineer. Adequate documentation is also necessary such that a technician can recognize fault symptoms on site. (Much loss of data in the English AVM systems was perpetuated because an adequate technical manual was not available.) Lastly, they feel that a good spare-parts inventory is a necessity but it is very expensive. This expense can be held down by using a central holding authority as a means of distribution.

The English feel that site selection is important to AVM operation and that hydraulic, aquatic growth, and temperature-salinity conditions have to be considered. They tend to avoid situations where oblique flow, weeds, and tidal or ponded water could cause potential problems.

RECENT DEVELOPMENTS

Chipps Island Study

The Sacramento River at Chipps Island near Pittsburg, Calif., has long been a strategic location for measuring the combined outflow of the heavily farmed Sacramento and San Joaquin Valleys. Almost all the outflow is channeled through this relatively narrow tide-affected reach of the river. Operation of the complex California Aqueduct system would be facilitated if a real-time continuous measurement of the net outflow could be achieved at this location. A detailed report by Smith (1969) suggested that a usable measurement of outflow could be made if a suitable AVM system were available.

The Chipps Island channel is about 1,000 m wide with a maximum depth of about 15 m. The path length for an AVM system was about 1,200 m, much of it traversing a cross section about 9 m in depth. Initially it was thought that a multipath system would provide needed accuracy, but the acoustical environment is complicated by variability in salinity and temperature gradients.

A twice-daily tidal prism moving through the channel produces discharges on the order of 8,500 m³/s both upstream and downstream. When freshwater outflow is

low, saltwater intrudes up the channel and salt concentrations on the order of 10,000 to 20,000 mg/L can result. Temperature gradients are also present because of (1) thermal loading from local industries; (2) differences in water temperatures of the Sacramento and San Joaquin River systems, that come together 3 mi to the east; (3) and differences in temperature of the upstream-migrating saline water from San Francisco Bay and the downstream-moving freshwater.

In 1978, transducers, operating at 100, 40, and 24 kHz were installed on the north and south shores of the channel to determine the reliability of acoustical transmissions over a long path in this tidal estuary. Transmissions were activated by a programed transmitter on the north shore and received signals were recorded on the south shore. Tests carried out over a period of about 60 days indicated highly variable attenuation of signal strength. These tests showed more reliable performance at lower frequencies and more consistent acoustic transmissions for paths placed near middepth. Correlations could not be established between performance and any of the parameters of stage, velocity, phases of the tidal cycle, wind and surface waves, or specific conductance.

A submarine cable was placed across the channel in 1979, and an AVM using 30 kHz transducers was installed for evaluation. Analysis of received acoustic signals showed frequent periods when received signals were greatly distorted, causing timing errors of unacceptable magnitude. When signal transmission was poor, the initial part of the received signal was attenuated below the threshold level of the timing circuitry and several cycles of the signal were missed before the timing period terminated. Data-quality checks, built into the AVM computer, could identify gross errors but would not eliminate bias associated with carrier-cycle timing error.

Work done by Henry Falvey of the Bureau of Reclamation in 1981 suggests that the principal cause of signal loss at the Chipps Island site is ray bending due to temperature and salinity gradients along the acoustic path. Falvey's computations, based on temperature and specific conductance observations near the north shore, show that the transmitted signals do not follow a straight line at the elevation of the transducers, but may in fact be reflected several times from the surface or the bottom. Figures 16 and 17, taken from an unpublished report by Falvey, show ray bending caused by salinity and temperature gradients that could occur at this site. In reality, the gradients exist simultaneously, the result being a very complex form of bending. The net effect could be the destruction of the received waveform, particularly the most important initial cycle. The primary implication of ray bending is that it invalidates the assumption of the unique relation between the velocity measured along a particular acoustic path and the mean velocity in the channel. For long path systems subject to thermal or con-

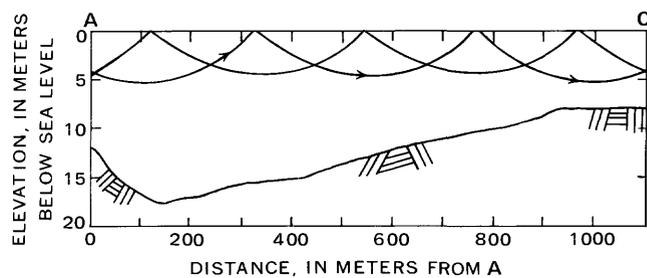


Figure 16. Upward-curving paths (radius=5 km) caused by a typical salinity gradient in the Sacramento River at Chipps Island, Calif. (modified from Falvey, 1981).

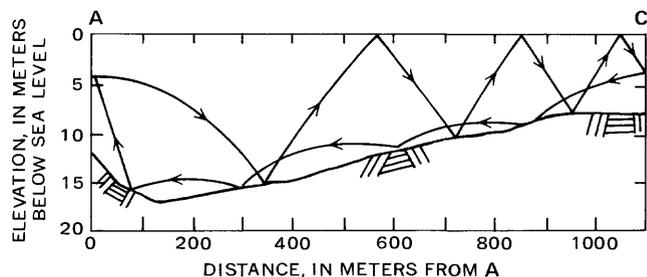


Figure 17. Downward-curving paths (radius=5 km) caused by a typical temperature gradient in the Sacramento River at Chipps Island, Calif. (modified from Falvey, 1981).

ductivity gradients, the received signals may traverse almost any path. Consequently, errors of approximately ± 5 percent may be anticipated in the relation between velocities defined by the acoustic system and the mean velocity in the cross section at this site. This error in gross computation of flow is approximately the magnitude of the total net flow and thus renders computation of net flow meaningless.

Use of the equipment at Chipps Island where typical estuary tidal conditions exist, shows that AVM systems can, however, be used effectively for measurement of gross tidal flows. Measurements made under these tidal conditions do not have the precision that can be obtained in more homogeneous streams. Long path systems are subject to larger errors than short path (less than 400 m) systems because the location of the actual acoustic path cannot be predicted.

Research in the Netherlands

The Dutch have been actively engaged in researching AVM systems and related techniques since 1975. Experiments in the wide, shallow channel of the Oosterschelde estuary proved to them the value of AVM systems. An acoustic path of 1,000 m was measured with 65 kHz transducers (Schmidt, 1978), and useful acoustical signals were received most of the time.

After careful assessment of error sources (Drenthen, 1981) and practical transducer locations in the field, the Dutch have drawn the following conclusions:

1. Most relatively straight and confined channels can be measured in one horizontal plane to within 5 to 10 percent accuracy for paths less than 1,000 m.
2. Transducer locations near the surface or bottom of a cross section are not practical because of signal bending and multipath problems.
3. A cross path is necessary where the angle of the acoustic path to the streamlines of flow cannot be determined accurately.
4. An additional path, which can be out of the water at low stages is necessary, when a large range of stage occurs.
5. *K* coefficients can be accurately determined by physical modeling techniques, and in situ measurements are, for the most part, unnecessary.

The Dutch have designed their own transceiver and transducer systems primarily for streamflow measurement in wide, shallow channels. At present, their model studies have defined velocity profiles in low-slope, low-velocity channels with surges. Future research will involve channels with bends; wind effect; and temperature, salinity, and sediment gradients. The Dutch have also experienced considerable problems with aquatic growth on transducer faces, and are experimenting with different epoxy resins and other approaches to discourage growth.

Comparison Testing of New Microprocessor Systems

Of the many recent developments incorporated by AVM manufacturers, the trend toward using microprocessors is probably the most important. This trend has reduced costs drastically and has simplified the electronics of AVM systems. New microprocessor systems do not necessarily replace minicomputer-oriented systems. Microprocessor AVM's record basic velocity-measurement data with less flexibility. However, microprocessor-based systems have a different flexibility because they are small, require little power, generally offer some self-test diagnostics, and do not require temperature control.

A test of microprocessor equipment by the Geological Survey is in progress using Westinghouse and ORE systems in the Willamette River near Wilsonville, Oreg. The purpose of the test, managed by the Hydrologic Instrumentation Facility and the Oregon District, is threefold; (1) to evaluate equipment performance and maintenance requirements, (2) to stress the systems and evaluate their weaknesses, and (3) to make recommendations to the Water Resources Division pertaining to future system configurations. The AVM units and the

shelter are shown in figure 18. Westinghouse equipment is on the right side of the top shelf and ORE equipment is just below on the next shelf. Other equipment includes an oscilloscope (for test purposes only), an analog recorder, a digital recorder, and associated timers. More facts about the system are given in table 4.

Testing of Doppler Systems

Tests of a Doppler system were made in 1979 on the California Aqueduct and the Sacramento River for the Geological Survey by Ametek, Straza Division. Doppler Sonar current profiling equipment used to define ocean currents in the vertical, was modified to operate as a streamflow meter and measure velocity along a horizontal segment. Results from these pilot tests have shown that this equipment is capable of obtaining some useful information.

Tests were made under favorable acoustic conditions, and velocity profiles in the horizontal were obtainable for 24 m of the 36 m width of the California Aqueduct and for 60 m of the 210 m width of the Sacramento River. Interference created by reflections from bottom and surface destroyed the competence of velocity detection beyond the aforementioned distances.

Distances to which the acoustic beam will effectively penetrate are directly related to the transducer beam width and the channel geometry. The effective directivity of the conical acoustic beam of the test equipment was 9 degrees. By reducing this beam width to 3 degrees, velocity along the total width of the Sacramento River could have been measured. However, construction of a transducer to accommodate 3 degrees would result in a probe of unacceptable physical proportions. It is also difficult to ascertain where in the vertical the backscattered frequency shift occurs and relate this information to a mean velocity.

Sediment loads in the streams were approximately 150 mg/L, a favorable condition for the Doppler tests. Greater sediment loads would undoubtedly decrease the penetration capabilities of the system, lesser sediment could eliminate operation entirely. More intensive testing is necessary to prove the application of Doppler equipment to streamflow measurement.

Future Applications

Recent developments in other areas of electronics should make AVM systems even more versatile. The need for a hardwire link between transducers (a high-cost item for long paths) will eventually be eliminated. Acoustic measurement of stage and cross section can be easily incorporated into AVM systems. Utilizing acoustics to pro-

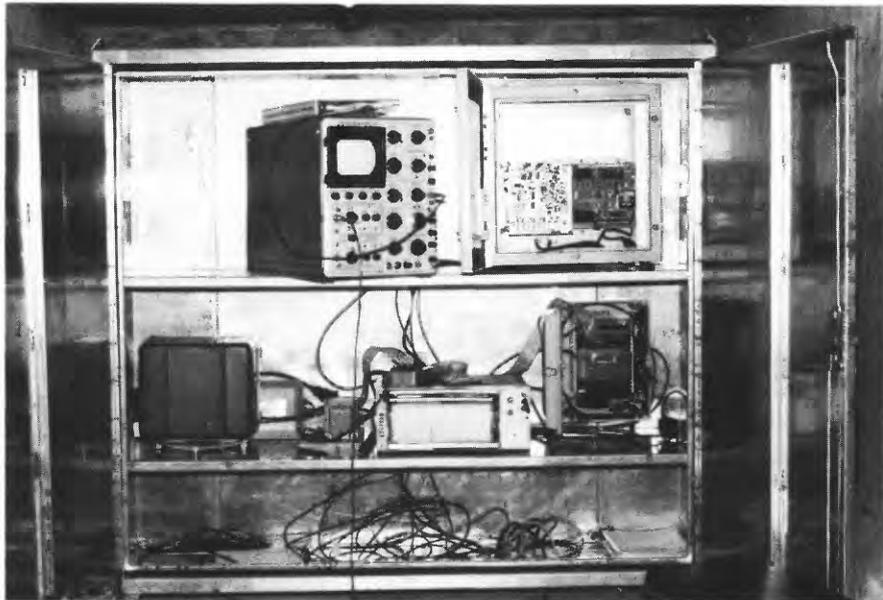


Figure 18. Shelter and equipment at the Willamette River test site.

vide an indication of suspended-sediment concentration is also a possibility.

Systems are now available that do not require a submarine cable link. Krupp-Atlas and ORE have designed responder systems that utilize independent transducers and simple logic components located on the bank opposite the primary electronics (see fig. 19). A signal can be transmitted downstream from transducer A along a diagonal path to transducer B. The received signal is then routed to a responder where it triggers a transmit signal with some minimal electronic delay (t_R). This signal travels downstream along another diagonal path from transducer C to transducer D and is received back in the primary electronics package where there is minimal delay (t_{PE}). There is additional time delay in the cabling that connects the transducers to the electronics. For the upstream traveltime the above procedure is reversed. Reciprocity is ensured because all paths traveled in the opposite directions are equal. Radio, radar, or laser telemetry could also be used as a replacement for the submarine cable link but development is needed. A responder-type system seems to offer more potential than radio, radar, or laser telemetry systems.

The electronics used in transmission and reception of acoustic pulses, associated timing, and scaling exists in all present equipment. Additional transducers are all that are required for additional velocity output. Systems are available that can record stage with either upward-looking (underwater) or downward-looking (air-mounted) transducers.

Signal transmissions are attenuated because of scattering by suspended-sediment particles. Monitoring the attenuation of the received signal provides an indication

of sediment concentration and should provide a usable index to help with the computation of sediment records at many locations. If proven, this scheme of monitoring sediment by use of AVM equipment could be incorporated, with minor modifications, in existing or future systems.

To date (1981), AVM systems have been too expensive for most field operations, but this is being changed by use of new microprocessor equipment. This equipment can now be used in many situations where use of AVM's was formerly cost prohibitive. Acoustic measurement of velocities is now economically feasible for use in remote areas, sand channels, ice-covered streams, and estuaries (to name only a few).

CONCLUSIONS

Acoustical measuring techniques in open channels are not used as frequently as in oceans and pipelines. Costs of acoustical equipment and its operation have been restrictive, and knowledge of how such systems work in a much more complicated environment than exists in either the ocean or in pipes is limited. The increased use of AVM systems in stream gaging is predicated on the continued need for accurate systems to measure streamflow at locations where there is no direct relationship between discharge and stage.

Measurement by acoustical means has proven to be a desirable method for determining discharge at problem sites. Acoustic measurement of velocity has the advantage of being nonintrusive and nonmechanical. AVM's have no practical upper limit of measurable velocity and

Table 4. --Acoustic-velocity installations (water-measurement only) with path lengths greater than 10 meters

Country	Nearest city or other location	River, canal, aqueduct, penstock, or other name	Date installed	Status	Transducer frequency (kHz)	Path length (meters)	Type of path	Acoustical anomaly	Discharge-rating method	Estimated accuracy (percent)	Output	Equipment Type
A.E.R.E. Harwell (Atomic Energy Research Establishment) Plessey Radar, Ltd.												
United Kingdom	Knapp Mill	River Avon	1974	Operating	100	48	Single	None	Current meter	3-5	Velocity, discharge	Display, paper punch
Do.	Kingston	River Thames	1974	do.	100	134	do.	Thermal gradient, sediment	do.	3-5	do.	Do.
Do.	Hempholme	River Hull	1975	do.	100	27	do.	None	do.	3-5	do.	Do.
Do.	Orton	River Nene	1975	do.	100	55	do.	Thermal and salinity gradients, sediment	do.	3-5	do.	Do.
Do.	Ashleworth	River Severn	1976	do.	100	12.6	2 path	Sediment, tide effect	do.	3-5	do.	Do.
Do.	Glen Faba	River Stort	1976	do.	100	30	Single	--	do.	3-5	do.	Do.
Do.	Sutton Courtney	River Thames	1976	do.	100	74	do.	Sediment	do.	3-5	do.	Do.
Do.	Bath	River Avon	1976	do.	100	51	do.	Thermal gradient, air entrainment	do.	3-5	do.	Do.
Do.	Ironbridge	River Dee	1977	do.	100	55	do.	None	do.	3-5	do.	Do.
Do.	Latchford	Manchester Ship Canal	1977	do.	100	53	do.	do.	do.	3-5	do.	Do.
Do.	Howley Weir	River Mersey	1977	do.	100	99	do.	Thermal and salinity gradients, sediment, vegetation and algae	do.	3-5	do.	Do.
Do.	Pickerings Cut	River Weaver	1978	do.	100	33	do.	Vegetation and algae	do.	3-5	do.	Do.
Do.	Kegworth	River Soar	1978	do.	100	52	do.	--	do.	3-5	do.	Do.
Do.	Blackwall Bridge	River Rother	1978	Experimental	100	46-58	2 path	Thermal and salinity gradients	do.	3-5	do.	Do.
Do.	Royal Windsor park	River Thames	1978	Operating	100	118	Single	None	do.	3-5	do.	Do.
Do.	Langport	River Parret	1978	do.	100	50	do.	Vegetation and algae	do.	3-5	do.	Do.
Do.	Weybridge	River Wey	1979	do.	100	50	do.	None	do.	3-5	do.	Do.
Do.	Bredon	River Avon	1979	do.	100	60	do.	--	do.	3-5	do.	Do.
Fokker Aircraft Industries												
Netherlands	Dordrecht	Noord River	1976	Operating	200	300	Cross reflection	--	Current meter	7	Velocity, discharge	Display, paper punch
Do.	Burghsluis	Easterscheldt-estuary	1977	Experimental	63	1,000	Single	Thermal gradient, sediment, vegetation and algae, tide effect, shipping	Theory	15	Discharge	Display, printer
Do.	Rijswijk	Rijn River Harbour	1979	do.	200	40	Cross reflection	None	do.	--	do.	Do.
Krupp-Atlas Elektronik												
West Germany	15 locations	(Rhine River Moselle River)					Single,					
Do.		(Elbe River)	1975		210	20 to 450	multi, and cross	Conductivity gradient, sediment, tide effect	Current meter	3-5	Velocity	Display, printer, paper punch
Do.		(Main River)	1980	Operating	210				Current meter, transducer	3	do.	Printer
Do.		(Weser River)			210	115	Single do.	None	Current meter, transducer	3	do.	Do.
Do.	Brugg	(Neckar River Aare River)	1972	do.	210	106	do.		Current meter, transducer	3	do.	Do.
Switzerland	Campelen	Zihlkanal	1975	do.	210	115	do.		Current meter, transducer	3	do.	Do.
Do.	Sugiez	Broyekanal	1975	do.	210	80	do.		Current meter	3	do.	Do.
Do.	Genf	Rhone River	1975	do.	210	78	do.		Current meter	3	do.	Do.
Do.	Ringgenberg	Aare River	1979	do.	210	51	Cross		Current meter	3	do.	Do.
United Kingdom	--	(Severn River)	1978	Portable	210	20-100	Cross	--	Current meter, theory	3	do.	Do.

Table 4.--Acoustic-velocity installations (water-measurement only) with path lengths greater than 10 meters--Continued

Country	Nearest city or other location	River, canal, aqueduct, penstock, or other name	Date installed	Status	Transducer frequency (kHz)	Path length (meters)	Type of path	Acoustical anomaly	Discharge-rating method	Estimated accuracy (percent)	Equipment	Type
Krupp-Atlas Elektronik--Continued												
Austria	--	Danube River	1979	Operating	210	200	Cross	Seiches and shipping	Theory	7	Velocity, discharge	Printer
Norway	--	--	1978	do.	210	70	Single	None	do.	7	Velocity	Do.
France	Paris	Seine River	1979	do.	210	150	do.	Heavy shipping	Current meter, theory	3	do.	Do.
Netherlands	3 locations	Canals	1976-79	do.	210	40-80	do.	Shipping	Theory	7	do.	Do.
Belgium	4 locations	do.	1978-80	Discontinued	210	70-100	Cross	do.	do.	7	Velocity, discharge	Printer, totalizer
Spain	--	--	1980	Operating	210	50	Single	None	do.	7	Velocity	Printer
Italy	--	--	1978	do.	210	40	do.	do.	do.	7	do.	Do.
Canada	Washago, Ontario	Severn River	1976	do.	210	70	do.	Measures under ice	Current meter	3	Velocity	Printer, paper punch

Ocean Research Equipment, Inc.

U.S.A.	Tracy, Calif.	(Old River (West Canal (East Canal Columbia River	1967	Operating	200	100	Single	None	Theory	1	Velocity only	Display
Do.	Grand Coulee, Wash.	Columbia River	1972	do.	80	205	do.	Air entrainment	Current meter	3	Velocity, discharge	Display, printer, paper punch
Do.	Pullman, Wash. Portland, Oreg.	Snake River Willamette River	1972	do.	80	320	do.	Sediment, air entrainment	do.	3	do.	Do.
Do.	Hemet, Calif.	Inlet Canal to Lake Skinner	1972	do.	80	276	do.	None	Current meter, routing	5	do.	Do.
Do.	Kettleman City, Calif.	California Aqueduct, check 21	1974	do.	500	13.8	9 path	do.	Theory	1	Discharge	Printer, totalizer
Do.	Los Banos, Calif.	California Aqueduct, check 12	1975	do.	500	45-60	8 path	do.	do.	1	do.	Do.
Do.	Boulder City, Nev.	Hoover Dam penstocks, Colorado River	1975	do.	500	45-60	do.	do.	do.	1	do.	Do.
Do.	The Dalles, Oreg.	Columbia River	1976	do.	500	13	4 ea. paths in 4 penstocks	do.	do.	1	do.	Display, printer, totalizer
Do.	Sacramento, Calif.	Sacramento River	1978	do.	100	402	Single	Temperature gradient	Current meter	3	Velocity, discharge	Display, printer, paper punch
Do.	Warsaw, Mo.	Osage River (Harry Truman Dam)	1978	do.	100	--	do.	Sediment	do.	3	do.	Do.
Do.	Wilsonville, Oreg.	Willamette River	1978	do.	100	200-284	6 path	Air entrainment, eddy flow	Current meter, theory	3	do.	Do.
Netherlands	Driemond	Amsterdam	1980	Experimental	200	155	Single	Sediment	Current meter	--	Velocity index	Display, paper punch
Do.	Dieze	Rijnkanaal	1976	Operating	200	110	Cross	Seiches and heavy shipping traffic	Theory	7	Discharge	Display, printer
Do.	Bunde	Julianakanaal	1977	Discontinued	200	90	Cross	Temperature gradient	do.	7	do.	Do.
Do.	Smeermaas	Zuid-Willemsvaart River	1977	do.	200	80	do.	do.	do.	7	do.	Do.
Do.	Rijswijk	Vliet Harbor	1977	Instruction and service	200	40	do.	Tide effect, seiches and heavy shipping traffic	do.	--	Velocity	Do.
Do.	Loozen	Zuid-Willemsvaart River	1980	Operating	200	50	do.	Seiches and heavy shipping	do.	7	do.	Do.

Table 4.--Acoustic-velocity installations (water-measurement only) with path lengths greater than 10 meters--Continued

Country	Nearest city or other location	River, canal, aqueduct, penstock, or other name	Date installed	Status	Transducer frequency (kHz)	Path length (meters)	Type of path	Acoustical anomaly	Discharge-rating method	Estimated accuracy (percent)	Output	Equipment Type
Ocean Research Equipment, Inc.--Continued												
New Zealand (3 meters)	Auckland	Waste-treatment channels	1979	Operating	200	15	Single	Sediment, vegetation and algae	Theory	--	--	--
Venezuela	Edelca	Caroni River	1980	--	100	--	--	--	--	--	--	--
Belgium	Chatelet	Sombre River	1980	Operating	200	54	Cross	None	Theory	7	Discharge	Display, printer
Tokyo Keiki Co., Ltd.												
Japan	Kurata Bridge	Naka River	1969	Operating	400	35	Single	None	Current meter	5	Velocity	Display
Do.	Ichikawa Bridge	Edo River	1969	do.	400	120	do.	do.	do.	5	do.	Do.
Do.	Noda Bridge	do.	1969	do.	400	100	do.	do.	do.	5	do.	Do.
Do.	Teiseki Bridge	Shinano River	1969	do.	400	270	do.	Tide effect	do.	5	do.	Do.
Do.	Yushima	Ibi River	1969	do.	400	120	do.	Sediment, vegetation and algae, tide effect	do.	5	do.	Do.
Westinghouse Electric Corp., Oceanic Division												
U.S.A.	Summersville, W. Va.	Summersville Dam penstock, Gauley River	1965	Operating	--	12	1 path ea. in 5 conduits	Cavitation noise	--	--	Discharge	Display, totalizer
Do.	Kettleman City, Calif.	California Aqueduct	1967	Discontinued	550	40	1 transducer traverse	None	Current meter, theory, transducer traverse	1	do.	Do.
Do.	San Luis Rey, Calif.	California Aqueduct	1967	do.	550	40	do.	do.	do.	1	do.	Do.
Do.	The Dalles, Oreg.	Columbia River	1967	do.	100	402	Single	Temperature gradient	Current meter	3	Velocity index	Display, printer, paper punch
Do.	Chicago, Ill.	Chicago Ship and Sanitary Canal	1968	Operating	550	70	4 path	Sediment, vegetation and algae	Theory (using average)	3	Discharge	Display, paper punch, voltage recorder
Do.	Wilsonville, Oreg.	Willamette River	1980	Experimental	200	155	Single	Sediment	Current meter	--	Velocity index	Display, paper punch
Canada	Niagara Falls, Ontario	Niagara River	1971	Discontinued	100	550	do.	Temperature gradient, shallow-depth river	do.	3-5	do.	Display, voltage recorder
Do.	Hudson Hope, B.C.	Peace River Dam penstock	1980	Operating	500	10	4 path	None	Theory	0.5	Discharge	Display

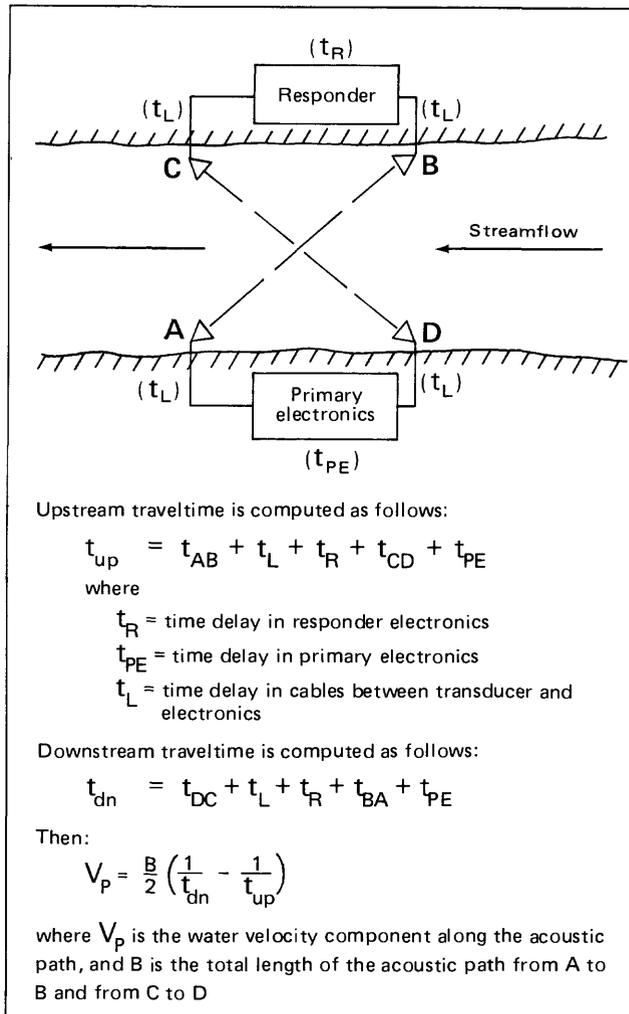


Figure 19. Components necessary for responder technique.

will normally operate with a resolution of ± 0.01 m/s. AVM's have been highly accurate and reliable, but only because of constant maintenance. It is anticipated that more reliable and less complicated equipment will decrease maintenance constraints.

To date, stream-based AVM systems have measured velocities along paths as long as 1,200 m. Discharge has been computed for numerous channel configurations, utilizing the line velocity as an index. Discharge computations are normally within the ± 5 percent accuracy range. Many AVM systems have utilized a multipath configuration to better define the mean velocity component.

AVM systems are normally used at sites where velocity distribution is somewhat regular; hence, they are normally used at sections where current-meter measurements can be made. As discussed previously, four factors affect acoustic performance: (1) multipath interference, (2) ray bending, (3) attenuation, and (4) changes in streamline orientation. However, in many instances,

these factors may not be serious limitations if a careful analysis of local conditions is made. AVM systems will work in a wide variety of conditions if they are used within their limitations.

Operational equipment has provided much practical experience and has helped to define limitations and indicate developmental needs. All systems have shown that, when operating under acceptable conditions, they perform well and are accurate. To date, the Geological Survey AVM systems have required considerable service stemming from: (1) temperamental teletype equipment; (2) power-sensitive computer equipment; and (3) computer sensitivity to dust, temperature, and humidity.

Instrumentation at The Dalles, Oreg., and Chipps Island, Calif., has given indications of what can and cannot be done when temperature and salinity gradients exist. Experience gained at three sites (Grand Coulee Dam, Wash., Lower Granite Dam, Wash., and Truman Dam, Mo.) have shown the necessity to define attenuation, especially with respect to entrained air or gas, before

locating an AVM system. Problems at the Truman Dam site indicate the necessity of being aware of streamline aberrations before placing transducers. Problems on the Sacramento River site at Freeport have shown the necessity to investigate electrical noise before specifying system requirements. Increased use of sophisticated electronic AVM systems (as well as other new hydrologic systems) demands more in-house technical expertise.

Past performance has shown that the serviceability pertaining to acoustic circuitry, has been excellent. Hopefully, microprocessor equipment will provide the cost-effective systems long desired and reduce the many logistic and maintenance constraints of the minicomputer systems. New signal-detection techniques and communication links may provide additional flexibility so that systems can operate under diverse conditions in rivers and estuaries. Demonstrations are necessary to show the feasibility of using this equipment in situations such as those involving ice-covered streams, sand channels, and estuaries.

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